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Journal of Sound and Vibration 311 (2008) 767–785

JOURNAL OF SOUND AND VIBRATION

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Annoyance caused by heavyweight floor impact sounds in relation to the autocorrelation function and sound quality metrics

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Received 7 August 2006; received in revised form 17 August 2007; accepted 24 September 2007
Available online 30 October 2007

Abstract

This study investigated objective and subjective evaluations of heavyweight floor impact sounds. The autocorrelation function (ACF) parameters and sound quality (SQ) metrics were used to explain the annoyance of heavyweight floor impact sounds. Sounds were generated by a bang machine and an impact ball and were measured in various rooms in apartments with different sound insulation treatments. Annoyance caused by the heavyweight floor impact sound was evaluated using the paired comparison method, with a wide range of objective measures. The effects of the objective measures on annoyance were examined by multiple-regression analysis. The relationship between annoyance and ACF parameters showed the following to be important for evaluating annoyance: sound energy $\Phi(0)$, variances of $\Phi(0)$ and the maximum ACF amplitude ϕ_1. In terms of SQ metrics, the important factors for evaluating annoyance were loudness and fluctuation strength. The results showed that floors with viscoelastic damping material reduced $\Phi(0)$ or loudness. Viscoelastic damping material also reduced ϕ_1, which is related to the dominance of the resonance frequency of the floor slab structure and its harmonics. Reduction of the floor impact level at the resonance frequency by viscoelastic damping material resulted in high sharpness.

1. Introduction

In apartment buildings, the predominate dwelling in Korea, floor impact sounds are mainly caused by walking, running and jumping, and are regarded as the most annoying type of noise in these buildings. The typical structure of an apartment building consists of box-frame-type reinforced concrete construction, with retaining walls instead of columns and beams. Often, this type of building is equipped with a unique underfloor heating system, called *Ondol*. Walking barefoot on a floor causes impact noise at low frequencies. To mimic high-heel tapping or the dropping of a lightweight object, the tapping machine was developed. The tapping machine is a lightweight impact source that produces impact sounds of predominantly high frequencies. To simulate and evaluate the sound of humans walking and running, heavyweight floor impact

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doi:10.1016/j.jsv.2007.09.029

sources, such as the bang machine (tire, Japanese Industrial Standard JIS A 1418-2:2000 [1]; Korean standard, KS F 2810-2 [2]) and the more recently developed impact ball (ISO 140-11 [3]; JIS A 1418-2:2000), have been used. The procedures for these measurements are determined by existing regulations, and these regulations also determine the evaluation method for each impact source. Floor impact sound is evaluated according to sound pressure levels and their frequency characteristics. Although the noise level is one of the most important parameters for the subjective evaluation of noise, and many studies try to find effective parameters to express human perception (mainly loudness) of the noises [4–6], objective parameters other than noise level and frequency characteristics may also affect the perception of the noise source.

It is likely that most of the factors affecting the perception of noise are related to temporal (loudness, pitch, timbre, and duration) and spatial sensations (sound localization and spatial impression) [7,8]. These sensations are closely related to the autocorrelation function/interaural cross-correlation function (ACF/IACF) parameters. It has been shown that information about the perceived pitch and strength (i.e., tonality) of complex sounds are extracted from the maximum peak in the ACF [7]. When signals contain only harmonics without the fundamental frequency, people hear the fundamental frequency as the pitch, which is referred to as the residue pitch, periodical pitch, subjective pitch, or virtual pitch. Residue pitch cannot be explained by the spectrum of the source signal, but it can be explained by the ACF of the source signal.

Several ACF-based models for predicting residue pitch have been proposed. These include the autocorrelation model of pitch perception, which was originally a ''duplex'' model [9], and three ''pattern recognition'' models that have been generally accepted since the 1970s [10–12] because the phase relation does not influence the pitch perception [10,13]. A pitch transformer, based on an ACF, detects the locations of peaks from the output waveform in each frequency band. The pitch strength is estimated from the height of the maximum peak extracted from the ACF form. The effectiveness of the pattern-transformation model has been examined using ripple noises in order to evaluate the validity with respect to the peripheral weighting model [14–16]. The loudness and annoyance of narrow-band noise are related to the decay rate of the ACF [7,17–19].

Information regarding source direction and spatial impression can be evaluated by the IACF [7,8]. Binaural measurements, which more closely approximate actual human listening conditions, better reflect the spatial attributes of noise. For example, the peak value of the IACF represents the degree of similarity of sound waves arriving at a person's ears and explain the degree of subjective diffuseness in a sound field. ACF/IACF parameters have been used to describe the acoustic properties of aircraft, trains, drainage, floor impact, and refrigerator sounds [20–25]. Continuous measurement of ACF/IACF parameters enables evaluation of fluctuation of sensations, and the effect of the fluctuation of these parameters on annoyance has been investigated [25–27].

Sound quality (SQ) metrics, originally proposed by Zwicker [28], were defined in consideration of the listener's perception and evaluation of sound quality. SQ metrics reflect both frequency and temporal masking through the application of equal loudness contours. Loudness is a single index calculated from the loudness chart based on the measured one-third octave-band levels of a noise. Sharpness is a metric that measures the annoyance of high-frequency components in a sound. Roughness and fluctuation strength describe the fluctuation of a low-frequency signal, and the target modulation frequencies for roughness and fluctuation strength are 70 and 4 Hz, respectively. Presently, only methods for calculating Zwicker loudness for stationary sound have been standardized [29]; however, current investigations by ISO/TC 43/SC 1/WG 9 are aimed at determining the parameters necessary for evaluating the psychoacoustical aspects of sound, especially the loudness of non-stationary sounds and pitch detection.

From his auditory experiments on subjects who were exposed to low-frequency sound, Tachibana et al. [30] suggested that loudness is an exact noise measure. Jeon et al. [31] used the ACF/IACF parameters of floor impact sound to investigate the similarity between human-made impact sound and standard impact sound, and then examined the relationship between either ACF/IACF parameters or SQ metrics and loudness. More recently, loudness and annoyance from floor impact sounds for different sound insulation treatments applied in rooms of apartment units have been investigated in terms of the impact sound pressure level [32]. Their study showed that sound insulation in both the floors and walls in a box frame-type reinforced concrete structure reduces loudness and annoyance. Nonetheless, an investigation of the relationship between annoyance and the ACF parameters and SQ metrics of floor impact sound is necessary.

Annoyance is a part of the psychological reaction to noise and is characterized by a general feeling of displeasure or an adverse reaction generated by noise [33]. When sounds are roughly equivalent in other attributes, such as timbre and duration, annoyance depends on the sound level. Therefore, considerable effort has been spent on noise-reduction technologies that reduce sound exposure levels. However, for sounds with widely different acoustical properties, annoyance cannot be predicted by sound level alone. For example, there exist sounds that have a level below exposure standards, but they may still be perceived as noisy or annoying in a given situation [23].

The purpose of the present study was to investigate the effects of the ACF parameters and SQ metrics on the annoyance of heavyweight floor impact sounds, in order to analyze the noise source in terms of human perception. Though the relationship between sound insulation treatments and sound level reduction has been clarified for lightweight impact sound, the same is not true for heavyweight impact sound. In addition, the frequency characteristics, duration and the attenuation characteristics of the heavyweight floor impact sound, may affect the perception of the residents. Therefore, the relationship between heavyweight impact sounds and their subjective evaluation are focused on in this study.

In this study, heavyweight floor impact sounds were measured in the rooms of apartments with different types of sound insulation treatments. The acoustical characteristics of the heavyweight impact sounds were clarified using the ACF parameters and SQ metrics. With respect to SQ metrics, we used the original definitions proposed by Zwicker, despite the fact that the floor impact sound is not stationary, and sharpness, roughness, and fluctuation strength are defined mainly for stationary noise and modulated pure tones and bandpass noises. By using these metrics, we tried to find parameters which describe human perception and explain their meaning in relation to the floor impact sound. Subjective tests were conducted to obtain values of annoyance. Then, the relationships between annoyance and objective measures were examined with multiple regression analysis.

2. Measurements of floor impact sound from heavyweight impact sources

2.1. Procedure

Floor impact sound was measured in various units of two types of apartments, each having different floor plans. Fig. 1 shows the various combinations of noise isolators tested. As shown in Fig. 1(a) (RI units, i.e., units with installed resilient isolators), the test apartment consisted of units connected vertically and horizontally from the 16th to the 20th floors. The floor area of each unit was about 100 m^2. RI$_f$ indicates the structural components of the treatments for the floor of the upstairs where the floor impact sounds were generated. "RI$_w$" and "RI$_c$", respectively, indicate the treatment of the walls and the ceiling of the room where the floor impact sounds were recorded. The resilient isolators, which consist mostly of polyethylene (PE) foam, were inserted between the reinforced concrete slab and the upper layer of the floor. This creates a "floating floor," structure, generally used for its effectiveness in controlling lightweight impact sounds. However, where heavyweight impact sound is the most annoying floor impact noise, the application of viscoelastic polymer damping materials to existing structures, via constrained damping layers, is an effective means for reducing heavyweight impact noise. Fig. 1(b) shows the location of the installed viscoelastic damping material (Visco units).

Damping materials absorb energy when subjected to longitudinal tension and compression. The materials' effectiveness depends on their storage modulus and loss factor. If a damping layer is properly constrained, it also absorbs deformation energy caused by shear and/or compression forces. These absorption characteristics depend on the stiffness of the upper and lower portions of the constrained damping layer. Detailed sections of RI unit (RI$_{fcw}$, the totally insulated structure) and Visco$_f$ unit are shown in Fig. 2.

The details of the sound insulation treatments for the floors in this study are listed in Table 1. RI and Visco units had reinforced concrete slabs of the same thickness (150 mm). The heavyweight impact sounds were generated with the bang machine and the impact ball at the central position of each room. According to ISO standards for evaluating floor impact noise levels, microphones were positioned either at fixed locations including the periphery of the room, or at varying locations using a moving microphone. However, the focus

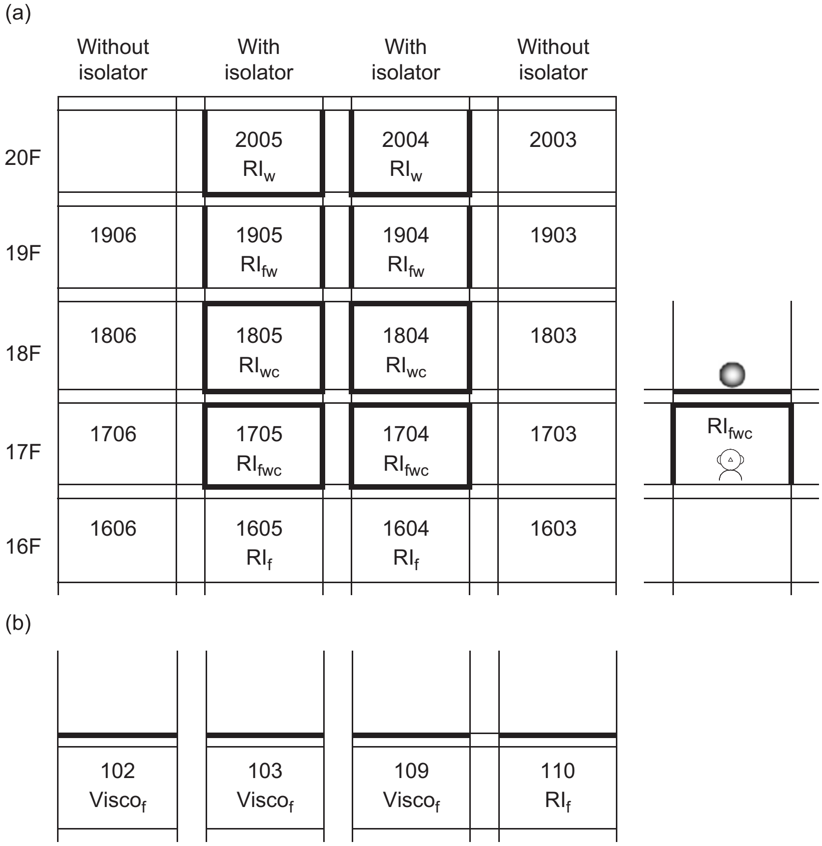

Fig. 1. Heavyweight impact noise reducing treatments: (a) Units with installed resilient isolators (RI); and (b) units with installed viscoelastic damping materials (Visco). Thick lines indicate location of resilient isolators and viscoelastic damping materials (f = floor of the above room, w = wall of the room, c = ceiling of the room). Right side of Fig. 1a shows an example of RI_{fcw}.

of this study was not the evaluation of floor impact sound levels, but was to evaluate the sounds heard by the lower floor tenants. Therefore, the heavyweight impact sounds were recorded binaurally through a dummy head (B&K 4100) positioned in the center of the downstairs room representing the typical listening location of a tenant. The distance from the ceiling, floor and walls to the dummy head were 2.1, 1.2, and 1.8–2.1 m, respectively.

A comparison between these impact sources and human-made impact sounds revealed that impedance, impact force and impact sound pressure level of the sound made by the impact ball were more similar to those of the human-made impact sound [34]. Examples of the waveform of the floor impact sounds are shown in Fig. 3. The floor of the Visco_f unit had a shorter time response and a lower amplitude compared with the floor of the RI_f unit, which had a longer response time and higher amplitude.

The measured data was evaluated in accordance with a single-number rating method using the inverse A-weighted impact sound pressure level, $L_{i,\mathrm{Fmax,AW}}$. Here, i refers to "impact," Fmax is the maximum sound pressure level measured by the sound level meter with the time constant "Fast", and AW is a consideration of the inverse A-weighting curve as shown in Fig. 4. To determine the $L_{i,\mathrm{Fmax,AW}}$, the measured maximum impact sound pressure levels ($L_{\max}$) were plotted against four-octave band frequencies from 63 to 500 Hz, according to JIS A 1419-2 [35]. The fitting procedure allowed for a total deviation of 8 dB above the inverse A-weighted reference curve (see Fig. 4) in each of the four octave measurement bands. The $L_{i,\mathrm{Fmax,AW}}$ of the floor was read as the impact sound pressure level at 500 Hz on the inverse A-weighted reference curve. The dummy head recording gave two sound signals, a left and a right channel signals. The arithmetic mean of the left and right channel is used to calculate $L_{i,\mathrm{Fmax,AW}}$.

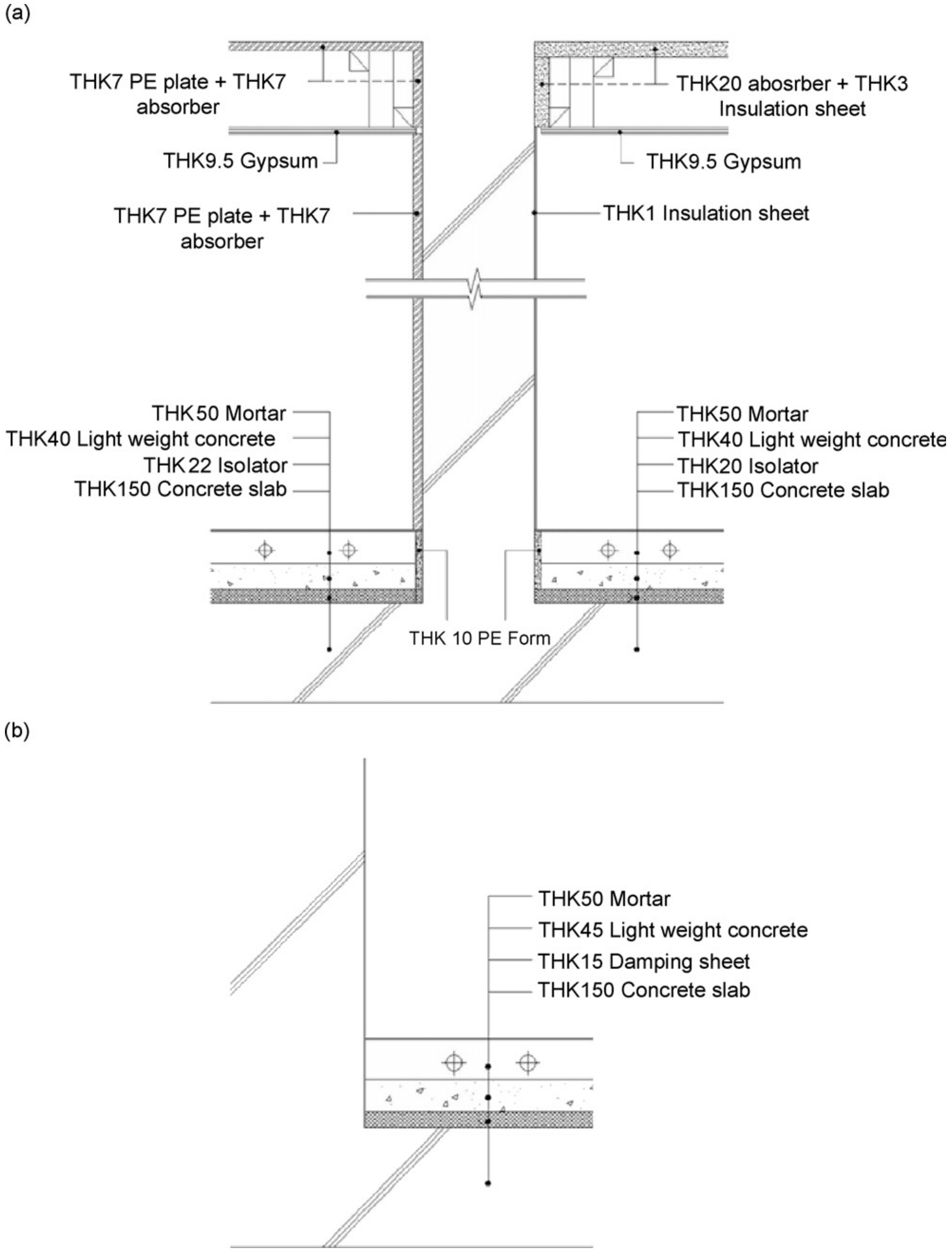

Fig. 2. Section details insulation treatments using: (a) noise isolators (RI) in the floor (f), walls (w) and ceiling (c); and (b) viscoelastic damping materials in the floor.

Fig. 5 shows the relationship between the $L_{i,\mathrm{Fmax,AW}}$ of the bang machine and the impact ball. The figure reveals a difference between the $L_{i,\mathrm{Fmax,AW}}$ for the resilient isolator and the damping material (comparison between RI and Visco units). It also shows the differences between the $L_{i,\mathrm{Fmax,AW}}$ for units with and without resilient isolators (within RI units). The impact noise levels were lowest for the floors of Visco$_\mathrm{f}$ units. A comparison of $L_{i,\mathrm{Fmax,AW}}$ with and without the resilient isolators in RI units indicated that the resilient isolators did not always reduce the noise impact level. These results are consistent with previous findings that isolators amplify low-frequency noises (below 100 Hz) generally produced by heavyweight impacts [36].

In the RI units, the $L_{i,\mathrm{Fmax,AW}}$ was larger for the bang machine than for the impact ball. On the other hand, the $L_{i,\mathrm{Fmax,AW}}$ of the bang machine was smaller than that for the impact ball in the Visco$_f$ units. The impact

Table 1
Details of the floor sound insulation treatments using (a) noise isolators (RI) and (b) viscoelastic damping materials (Visco)

Room	Sound insulation treatment details
(a) RI units	
Plain floor	Reinforced concrete slab (150 mm) + light-weight concrete (60 mm) + heating coil (hot water pipe) + cement mortar (50 mm)
With isolator	Reinforced concrete slab (150 mm) + impact isolator (20 mm) + light-weight concrete (45 mm) + heating coil (hot water pipe) + cement mortar (50 mm)
(b) Visco units	
102	Reinforced concrete slab (150 mm) + light-weight concrete (45 mm) + viscoelastic damping material (15 mm) + heating coil (hot water pipe) + cement mortar (50 mm)
103	Reinforced concrete slab (150 mm) + viscoelastic damping material (15 mm) + light-weight concrete (45 mm) + heating coil (hot water pipe) + cement mortar (50 mm)
109	Reinforced concrete slab (150 mm) + viscoelastic damping material (20 mm) + light-weight concrete (40 mm) + heating coil (hot water pipe) + cement mortar (50 mm)
110	Reinforced concrete slab (150 mm) + resilient isolator (20 mm) + light-weight concrete (40 mm) + heating coil (hot water pipe) + cement mortar (50 mm)

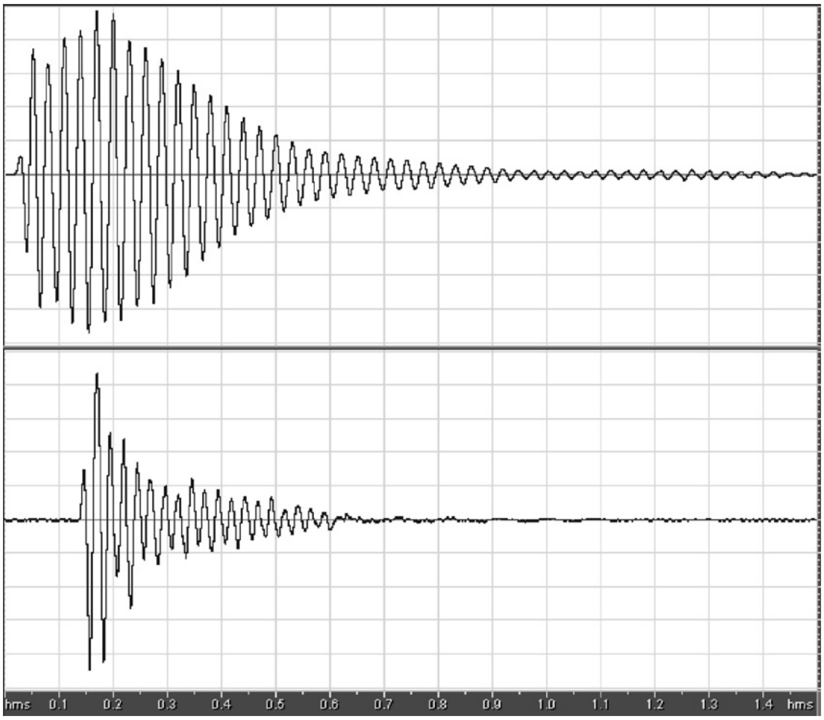

Fig. 3. Typical floor impact sound waveforms for the bang machine for (a) RI_f and (b) Visco_f units.

force of the bang machine at 63 Hz was higher than that at other higher frequencies. In addition, the impact force of the impact ball was higher than that of the bang machine at 125 Hz and higher frequencies [36]. Even though the viscoelastic damping material increased the resonance frequency of the floor slab structure (above 23 Hz) and reduced the floor impact sound level at the resonance frequency, the $L_{i,\mathrm{Fmax,AW}}$ for the impact ball was still determined by the sound pressure level at 125 Hz. This is the reason for the difference in behaviors of the resilient isolators and the damping material.

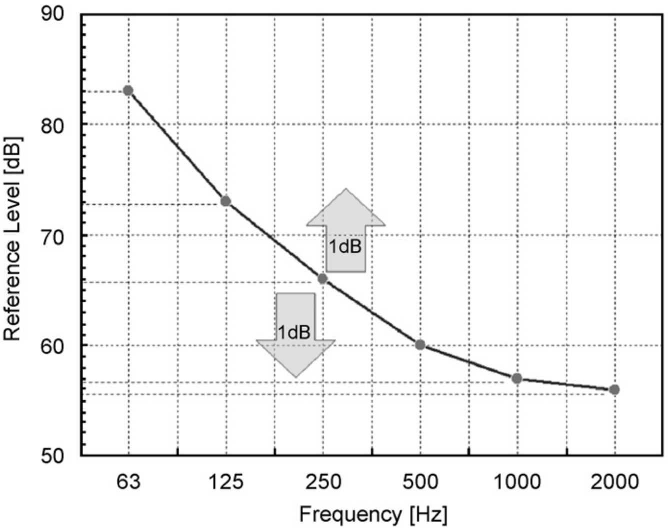

Fig. 4. Inverse A-weighted reference curve (JIS A 1419, Part 2 [35]).

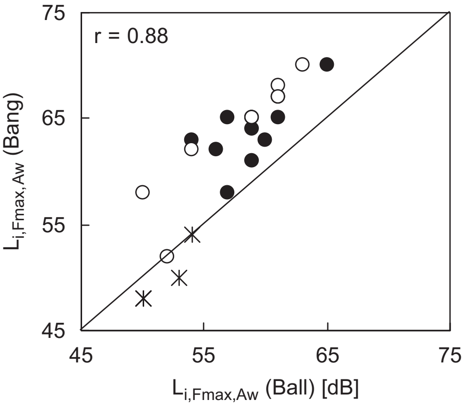

Fig. 5. Relationship between the bang machine and the impact ball $L_{i,\mathrm{Fmax,AW}}$ values: ●: with noise isolators; ○: without noise isolators; and ✳: viscoelastic damping material.

2.2. ACF parameters

ACF parameters ($\Phi(0)$, τ_1, ϕ_1, and τ_e) were used to clarify the acoustical characteristics of the floor impact sound. The ACF of a given source signal $p(t)$ is defined by

$$\Phi(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} p'(t)p'(t+\tau)\mathrm{d}t, \tag{1}$$

where $p'(t) = p(t)*s(t)$, $s(t)$ is ear sensitivity, which consists of the head-related, the ear canal, and the middle ear transfer functions [37–39]. For convenience, $s(t)$ is chosen as the impulse response of an A-weighted network. It has been reported that an A-weighted impact sound pressure level is a good measure for psychoacoustic investigations [40]. The floor impact signals were recorded by a dummy head. The microphones of the dummy head (B & K 4100) were attached at the entrance of both ears. Thus, the recorded signals included the head-related transfer function effect, but did not consider the external auditory canal, or the middle ear transfer functions. Therefore, the A-weighting network was still suitable for the approximation of ear sensitivity.

The ACF is identical to the power density spectrum $P(\omega)$, so

$$\Phi(\tau) = \int_{-T}^{+T} P(\omega)\,\mathrm{e}^{\mathrm{j}\omega t}\,\mathrm{d}\omega \tag{2}$$

and

$$P(\omega) = \int_{-T}^{+T} \Phi(\tau)\,\mathrm{e}^{-\mathrm{j}\omega t}\,\mathrm{d}\tau. \tag{3}$$

Thus, the ACF and the power density spectrum mathematically contain the same information. The normalized ACF is defined by

$$\phi(\tau) = \Phi(\tau)/\Phi(0). \tag{4}$$

The concept of a short-time moving ACF is illustrated in Fig. 6. The ACFs are calculated at every given integration interval $2T$. Because a moving analysis is effective in describing temporal properties such as transition, decay and fluctuation of a sound, the start of each integration interval was delayed for a short time (the moving step). The fine structures of the ACF were extracted as physical factors. The definitions of the ACF parameters are illustrated in Fig. 7. The ACF in the figure was calculated from the floor impact sound used in this study. The first ACF parameter is energy at the origin of the delay, $\Phi(0)$. The second and third ACF parameters are the delay time and the amplitude of the first dominant peak of the normalized ACF, τ_1, and ϕ_1, respectively (Fig. 7a). The effective duration, τ_e, is the fourth ACF parameter, and it is defined by the 10-percentile delay, representing the degree of persistence of a signal or reverberation within the source signal itself. For pure tone sound, the ACF is also a cosine function that continues infinitely. If the signal is white noise, the normalized ACF is unity at $\tau = 0$ and then falls instantly to 0. Sounds such as daily noises, music and speech are located between pure tone and white noise. For example, the τ_e of bandpass noise increases as the bandwidth decreases [17]. If the sound has one or more sharp maxima in the frequency domain, τ_e becomes long. The variable, τ_e, represents tone-to-noise ratio of the sound source. Fig. 7(b) shows the absolute value in the logarithmic form as a function of the delay time and demonstrates a procedure for obtaining the effective duration of the analyzed ACF. Considering the exponential decay of an ACF envelope in the range of early

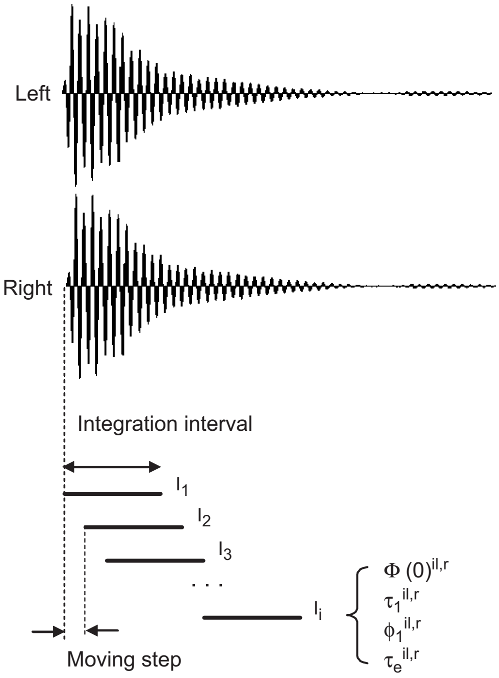

Fig. 6. Concept of short-time moving ACF.

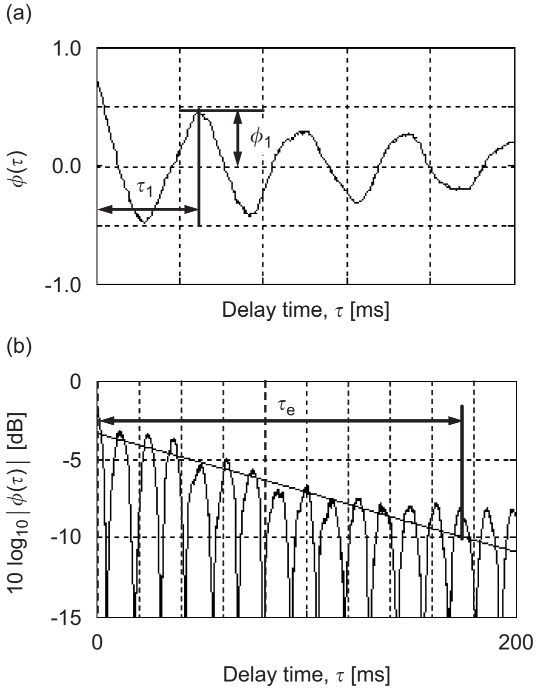

Fig. 7. Definition of ACF parameters. The ACF was calculated from a floor impact sound used in this study. (a) τ_1 and ϕ_1. (b) τ_e.

delay time, the envelope decay of the initial part of ACF may be linear in most cases [41]. The straight-line method was used for fitting the local maximum of each interval $\Delta\tau$. The normalized ACF is obtained by the FFT algorithm with the Wiener theorem after obtaining the power density spectrum for each signal with $2T$. Then, the envelope of maxima of $\Delta\tau = 20$ ms intervals may be drawn by a straight-line regression for a delay range shorter than 100 ms.

When investigating the temporal properties in detail, a shorter $2T$ is better than a longer $2T$. However, in cases where the signal contains many low-frequency components, such as floor impact sounds, the decay slope of the envelope of the ACF inclines gently. In order to obtain the decay slope for the calculation of τ_e, the $2T$ needs to be 0.5 s or longer. In this study, $2T$ was chosen to be 0.5 s and the running step was 10 ms. Values of $2T$ longer than 0.5 s are too long for the calculation because the amplitude of each floor impact sound decreases 10 dB relative to the maximum up to 0.5–0.6 s. All ACF parameters, except for τ_e, were calculated with different $2T$ values (0.1, 0.2, 0.3, 0.4 and 0.5 s). The resulting ACF parameters did not differ significantly (1.8 dB for $\Phi(0)$, 0.1 for τ_1 and 0.06 for ϕ_1) except for $2T = 0.1$ s. Even though $\Phi(0)$ and ϕ_1 slightly decreased as 2T increased, the correlation coefficient of the ACF parameters for $2T = 0.5$ s and $2T = 0.1$, 0.2, 0.3 or 0.4 was more than 0.95, except for $2T = 0.1$ s. The average measures obtained for the signals in the left and right ear and those in the range 0.0–0.5 s were investigated.

The relationship between the ACF parameters of the bang machine and the impact ball are shown in Fig. 8. As shown in Fig. 8(a), $\Phi(0)$ was smaller than $L_{i,\mathrm{Fmax,AW}}$. This was because $\Phi(0)$ included the tail (attenuation part) of the impact sound as well as the initial part, while $L_{i,\mathrm{Fmax,AW}}$ was calculated only from the maximum sound level. The impact sounds measured in the Visco$_f$ unit had a smaller $\Phi(0)$ for both the bang machine and the impact ball. In contrast to the $L_{i,\mathrm{Fmax,AW}}$ results, the $\Phi(0)$ for the bang machine was always greater than that for the impact ball. The floor impact sound levels of the bang machine always had a longer response time than the impact ball due to the higher impact force level regardless of the floor insulation treatment. This is the reason for the differences in the $L_{i,\mathrm{Fmax,AW}}$ and $\Phi(0)$ values. The correlation coefficient of $\Phi(0)$ for the bang machine and the impact ball was 0.87.

The correlation coefficient of τ_1, which corresponds to the perceived pitch of the sound, for the bang machine and the impact ball was 0.76, as shown in Fig. 8(b). The difference between sound insulation

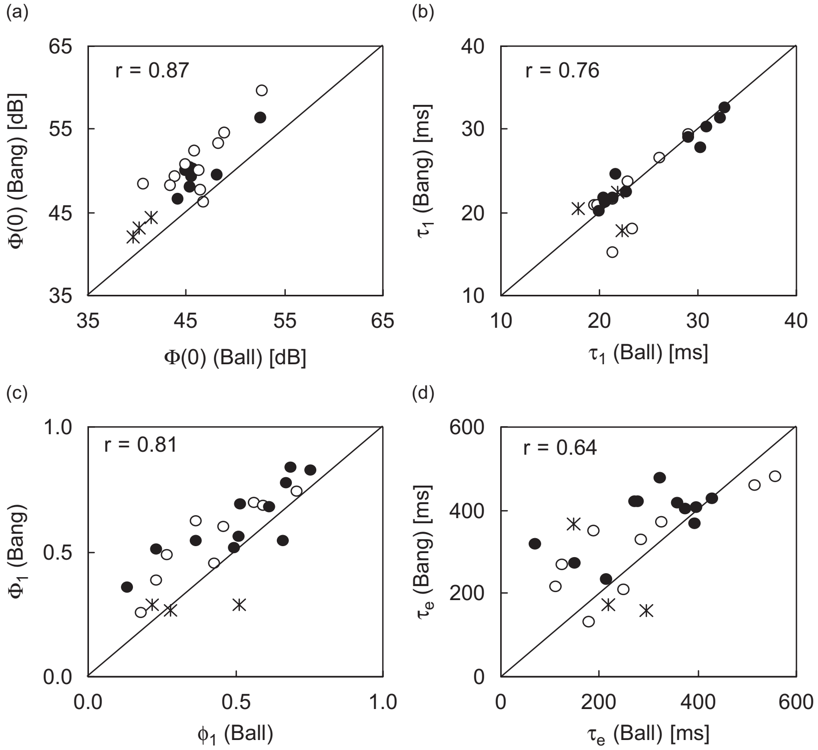

Fig. 8. Relationship between the ACF parameters for the bang machine and impact ball. (a) $\Phi(0)$, (b) τ_1, (c) ϕ_1, and (d) τ_e. ●: with noise isolators; ○: without noise isolators; and ⚹: viscoelastic damping material.

Table 2
Resonance frequencies of the unit structures calculated from the ACF of vibration signals and dominant frequencies calculated from τ_1 for viscoelastic damping materials (Visco units)

Room	Source	Resonance freq. (Hz)	$1/\tau_1$ (Hz)
102 (Visco$_f$)	Bang	24	44
	Ball	25	45
103 (Visco$_f$)	Bang	29	41
	Ball	29	46
109 (Visco$_f$)	Bang	33	46
	Ball	33	46
110 (RI$_f$)	Bang	20	36
	Ball	20	35

treatments may be described by τ_1 regardless of the type of impact source. The inverse of τ_1 corresponds to the frequency of the pitch. In RI units, a longer τ_1 (>29 ms), that is, a lower perceived pitch, was observed for the sound insulation treatment that included both the floor and the walls (RI$_{fw}$, and RI$_{fcw}$). In contrast, the floors of Visco$_f$ units produced impact sounds with shorter τ_1 values. As shown in Figs. 8(c) and (d), the values of ϕ_1 and τ_e for the bang machine were larger than those for the impact ball. The correlation of ϕ_1 and τ_e for the bang machine and the impact ball was 0.81 and 0.64, respectively.

Floors of the Visco$_f$ units produced impact sounds with smaller ϕ_1 and τ_e for both the bang machine and the impact ball, suggesting that viscoelastic damping material effectively reduces the lower-frequency component, causing the higher-frequency component to become alternatively dominant. Table 2 compares the resonance frequencies calculated from the ACF of vibration signals and the frequencies calculated by the τ_1 of the impact sounds. Both the resonance frequency and the inverse of τ_1 for the floors of the Visco$_f$ units are higher than

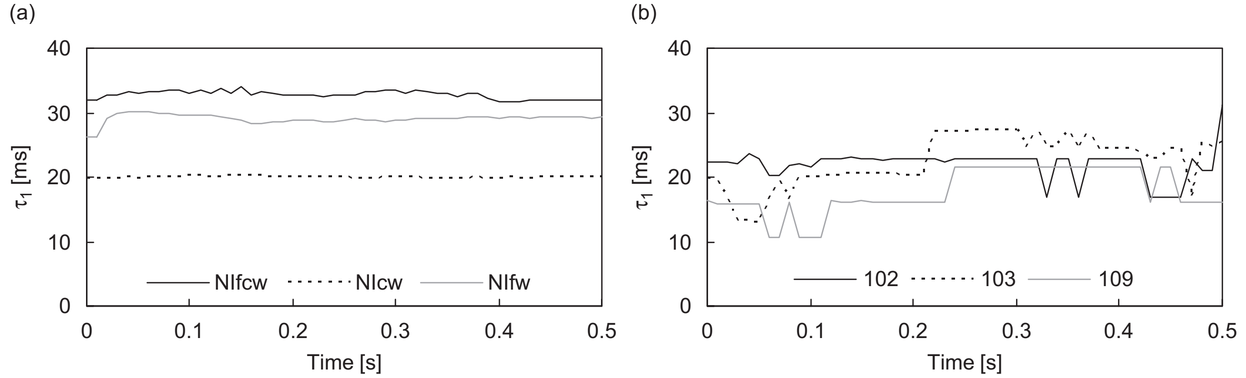

Fig. 9. Examples of the running τ_1 of impact sound generated by the impact ball: (a) τ_1 for floors with isolators. (b) τ_1 for floors with viscoelastic damping material.

those of RI_f because viscoelastic damping materials affect resonance and its center frequency and half-width. Incorporating various resonance curves of basic second-order resonators, such as Helmholtz resonators, into ACF evaluation would give similar changes of ϕ_1 and τ_1.

In this study, the initial 0.5 s of the floor impact sound was analyzed by the ACF, $2T = 0.5$ s with the moving step of 10 ms, which resulted in 51 running ACF parameters being obtained for each sound. As shown in Fig. 9, temporal fluctuation of τ_1 was observed for the floor of the Visco_f units, while the running τ_1 of the floor with a resilient isolator had less fluctuation. As shown in Fig. 2(a), impact isolators were installed on the top of the structural slab and inserted between the floating floor slab and the walls such that the floating floor slab was completely isolated from both vertical and horizontal translations. In contrast, viscoelastic damping materials were installed only on the top of the structural slab such that the edges of the upper structure touched the walls (Fig. 2(b)). Thus, the structure of the buffer located between the floor and the walls can affect the behavior of τ_1.

The relationship of the variance of the ACF parameters for the bang machine and the impact ball are shown in Fig. 10. The correlation of the variance of $\Phi(0)$ (VAR_$\Phi(0)$) for the bang machine and the impact ball is 0.65, and the VAR_$\Phi(0)$ for the floors with viscoelastic damping material is smaller than for those with isolators. With respect to VAR_τ_1, the values for the floor with viscoelastic damping material are greater than those with isolators. The correlation of VAR_τ_1 for the bang machine and the impact ball is 0.83. Lastly, with respect to VAR_ϕ_1 and VAR_τ_e, the correlation between the values for the bang machine and the impact ball is not significant ($r < 0.62$).

2.3. Sound quality (SQ) metrics

Sound quality (SQ) metrics (loudness, sharpness, roughness, and fluctuation strength) are also used to clarify the acoustical characteristics of floor impact sounds. A procedure for calculating SQ metrics has not yet been standardized, and thus the results calculated by one software package may differ from those obtained by others. For the present study, these metrics were calculated with Pulse Software (Brüel&Kjær). The concept of SQ metric calculation is illustrated in Fig. 11. For the calculation of roughness and fluctuation strength, the time interval between spectra was set at 5 ms. Specific roughness and fluctuation strength values were calculated from the temporal variation of loudness at each Bark band, while the mean values of loudness and sharpness were used to describe the acoustical property of the sound. The term loudness can be used for both objective and subjective measures. If loudness is obtained by a subjective matching test or a subjective magnitude estimation procedure, loudness is a subjective measure. Here, loudness of a given sound was computed using the sound pressure levels in one-third octave bands according to ISO [29], and was not obtained by subjective evaluations. Thus, in this regard loudness is an objective measure. The purpose of this study was to determine which objective measure or measures are related to the subjective evaluation (annoyance) of the floor impact sound.

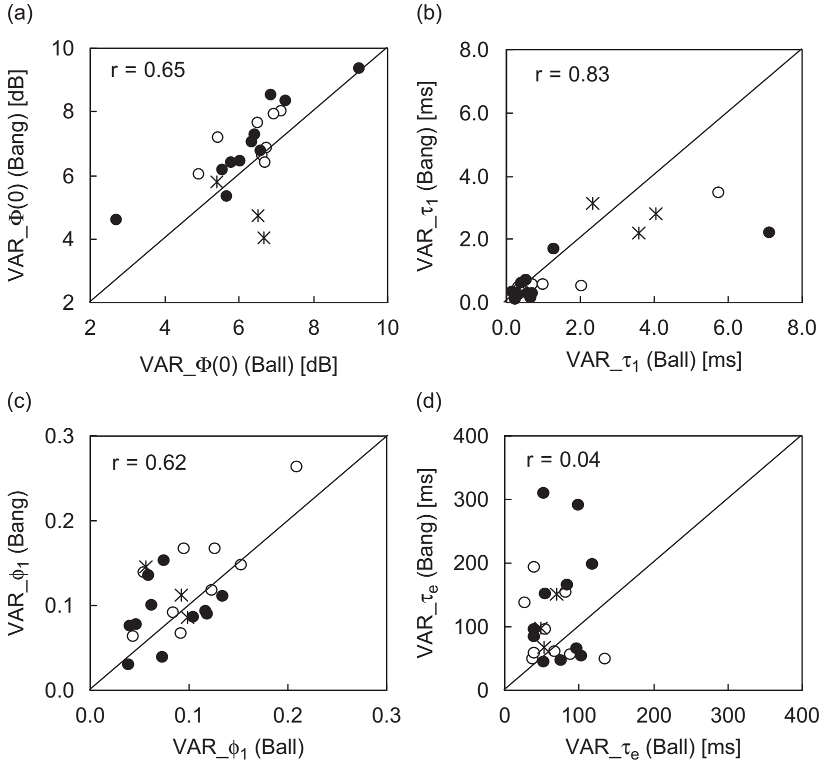

Fig. 10. Relationship between the variance of ACF parameters for the bang machine and the impact ball: (a) variance of $\Phi(0)$; (b) variance of τ_1; (c) variance of ϕ_1; (d) variance of τ_e. ●: with noise isolators); ○: without noise isolators; and ✳: viscoelastic damping material.

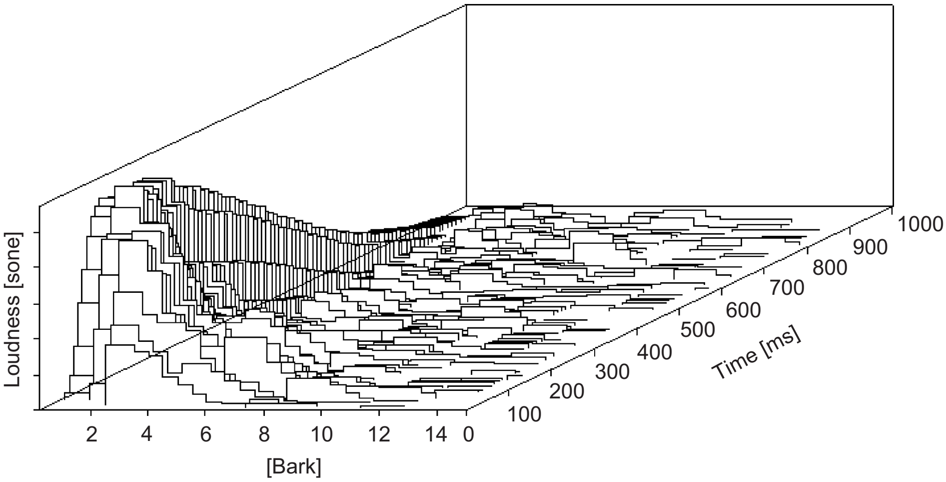

Fig. 11. Concept for calculating SQ metrics. The spectrum was calculated at 5 ms intervals.

Fig. 12 shows the relationship between the SQ metrics for the bang machine and the impact ball. Fig. 12(a) shows that loudness for the bang machine is greater than that for the impact ball. The result of loudness indicated that the floors of Visco$_f$ units reduced the impact noise level. The behavior of loudness was similar to that of $\Phi(0)$, with a correlation of 0.94 between loudness and $\Phi(0)$. The main component of the loudness of the floor impact sound was below 4 bark. As shown in Fig. 12(b), for the bang machine, sharpness, which corresponds to the location of the first moment (the center of gravity) for the weighted specific loudness, is

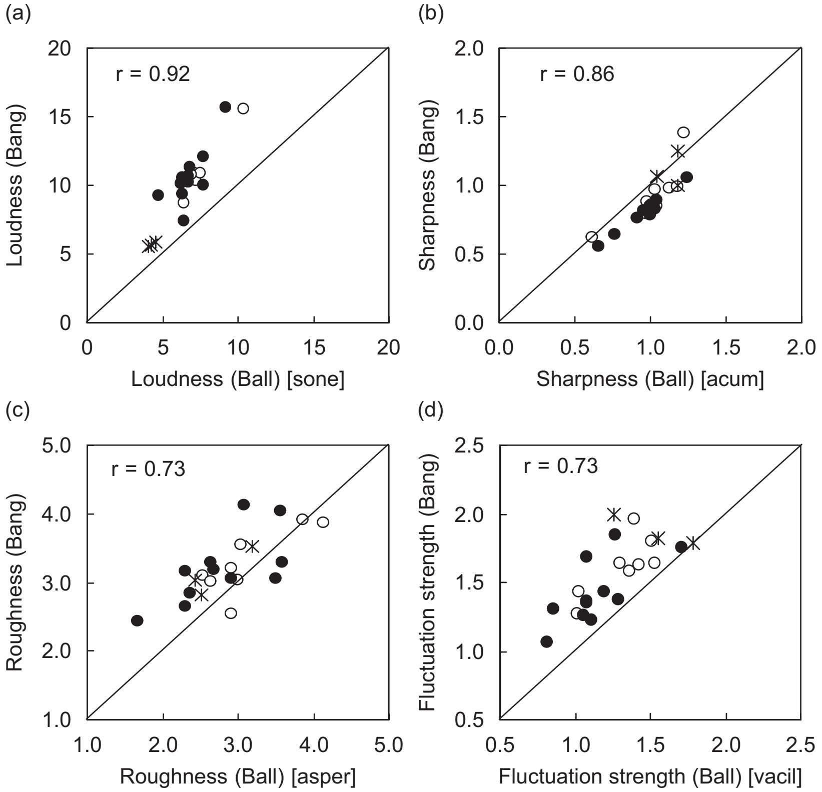

Fig. 12. Relationship between SQ metrics for the bang machine and the impact ball. (a) loudness: (b) sharpness, (c) roughness, and (d) fluctuation strength. ●: with noise isolators; ○: without noise isolators; and ✳: viscoelastic damping material.

slightly lower than that for the impact ball. At lower frequencies, the impact sound level is reduced by the viscoelastic damping material, while at higher frequencies the sound level is relatively increased. Thus, floors of Visco$_f$ units produced higher values of sharpness than floors with resilient isolators under these experimental conditions. In addition, sharpness had a certain correlation with ϕ_1 and τ_e ($r = -0.75$ and -0.78, respectively).

Roughness and fluctuation strength for the bang machine are higher than those for the impact ball (Figs. 12c and d). Floors of Visco$_f$ units produced higher fluctuation strength than those with resilient isolators. The RI units with sound insulation treatments in the floor had smaller fluctuation strength; however, with respect to roughness, there was not a clear difference between different sound insulation treatments. These results indicate that fluctuation strength, as opposed to roughness, more clearly reflects the differences between sound insulation treatments.

3. Annoyance in relation to objective measurements

3.1. Procedure

Annoyance was evaluated by the paired comparison method. Each of the eight floor impact sounds generated by the bang machine and the impact ball were chosen to cover a wide range of ACF parameters and SQ metrics. The source signals were presented through headphones (Sennheiser HD600). The headphones have a frequency response of 16–30000 Hz ± 3 dB. To confirm the objective parameters under experimental conditions, the signals presented by the headphones were recorded through a dummy head and the ACF parameters and SQ metrics of the signals were calculated. When the signal recorded through the dummy head was reproduced by the headphones and was recorded through the dummy head, the influence of the small part of the external auditory canal (inner portion of pinna) was repeated twice, however, there was good agreement between the two values for each ACF parameter and SQ metric.

The average differences of the $\Phi(0)$, τ_e, τ_1, and ϕ_1 for the signals recorded in rooms and reproduced by headphones were 0.17 dB, 5.7 ms, 0.13 ms and 0.007, respectively. The average differences for the loudness, sharpness, roughness, and fluctuation strength were 0.013 sone, 0.006 acum, 0.304 asper, and 0.026 vacil, respectively. The difference in roughness was larger than those of the other SQ metrics due to the variation in higher frequency ranges; however, the roughness in the frequency ranges below 6 bark (main component of floor impact sounds) showed that the average difference was, at most, 0.088 asper. The head-related transfer functions of the dummy head and each listener's head were not exactly the same. However, in a previous study it was shown that the differences between the acoustical parameters measured using the dummy head and human heads were within the difference limens except at the high-frequency ranges [42]. Therefore, the sounds presented by the headphones in our study are regarded as actual floor impact sounds. In the later regression analyses, the ACF parameters and SQ metrics of the signals presented by headphones and recorded through a dummy were used as the sounds that listeners actually listened to.

A test session consisted of 28 pairs of stimuli for the two heavyweight impact sources (bang machine and impact ball) at two sound levels (45 and 55 dB) realized as minimum and maximum jumping noise levels. The duration and silence interval between stimuli, which consisted of two repeated noises, was approximately 4.3 and 0.5 s, respectively. Each pair of stimuli was presented in random order separated by an interval of 3 s, which was the allotted time for the subject to respond. Test sessions lasted approximately 5.6 min, and a total of 40 subjects (20 university students and 20 housewives) who had normal hearing participated in the test.

The sound level for this experiment was fixed at a constant $L_{i,\mathrm{Fmax,Aw}}$. Subjects were seated in a sound-proof chamber and asked to judge which one of two stimuli they perceived to be more annoying as floor impact sounds. The subjects were asked to imagine the situation that they were in their own living environments. If an absolute level or absolute judgment were the subject of study, the experimental environment should be similar to that of an actual living room. However, the focus of this study was to investigate the relative comparison of impact sounds according to different sound insulation treatments. Therefore, the subjects were seated in a sound-proof chamber without tasks such as reading or listening to music. In this experimental condition, the sound level in terms of the $L_{i,\mathrm{Fmax,Aw}}$ was fixed. Even though this condition makes comparisons of loudness difficult, subjective judgments, such as annoyance, are easier.

3.2. Results

Forty responses to each of the two impact sources and two sound levels were obtained. Consistency tests indicated that 35 of 40 subjects had a significant ($p<0.05$) ability for distinguishing between various degrees of annoyance. The test of agreement indicated that there was a significant ($p<0.05$) agreement among subjects. A scale value of annoyance was developed by applying the law of comparative judgment (Thurstone's case V [43]). The results of a one-way ANOVA test showed that there was no significant difference between the scale values for the student and housewife groups ($p>0.84$). Thus, the scale values of annoyance were averaged across the 35 subjects. For the subjective test, the sound level of all of the stimuli was fixed at a constant $L_{i,\mathrm{Fmax,Aw}}$; however, differences were observed for $\Phi(0)$ and loudness. The correlation matrix between subjective annoyance and objective measures used in this study are listed in Table 3. To calculate the effects of each objective parameter on annoyance, multiple regression analyses were conducted using a linear combination of either ACF parameters or SQ metrics.

Table 3(a) shows that for all cases, there was a positive correlation between the ACF parameters $\Phi(0)$ and VAR_$\Phi(0)$, and scale values, and a negative correlation between VAR_ϕ_1 and the scale values. Thus, these three variables were selected for the multiple regression. If the resonance frequency and its harmonics indicate sharp amplitude peaks, ϕ_1 becomes large. In this case, a listener perceives a clearer pitch. It was confirmed that the regression model using these three parameters gave the highest regression coefficient. The standardized partial regression coefficients for variables a_1, a_2, and a_3 in Eq. (5) were 0.61, 0.15, and −0.46, respectively. These coefficients were statistically significant ($p<0.05$ for a_1, a_2, and a_3).

$$\mathrm{SV}_{\mathrm{annoyance}} \approx a_1\Phi(0) + a_2\mathrm{VAR\_}\Phi(0) + a_3\mathrm{VAR\_}\phi_1. \tag{5}$$

Table 3
Correlations between annoyance and the mean and variance of the ACF parameters (a) and SQ metrics (b)

	Bang (45 dB)	Bang (55 dB)	Ball (45 dB)	Ball (55 dB)	Total
(a) ACF parameters					
$\Phi(0)$	0.52	0.76	0.62	0.82	0.66
τ_e	–0.30	0.33	0.14	–0.20	–0.01
τ_1	0.44	0.33	–0.11	–0.18	0.02
ϕ_1	0.27	0.13	0.09	–0.49	0.00
VAR_$\Phi(0)$	0.39	0.70	0.66	0.24	0.13
VAR_τ_e	–0.64	–0.65	0.08	–0.26	–0.39
VAR_τ_1	–0.69	–0.04	0.57	–0.20	–0.02
VAR_ϕ_1	–0.04	–0.69	–0.02	–0.26	–0.29
(b) SQ metrics					
Loudness	0.56	0.77	0.78	0.70	0.66
Sharpness	–0.53	–0.59	–0.25	0.00	–0.19
Roughness	–0.09	–0.17	0.75	0.47	0.22
Fluctuation Strength	0.29	0.42	0.76	0.67	0.38

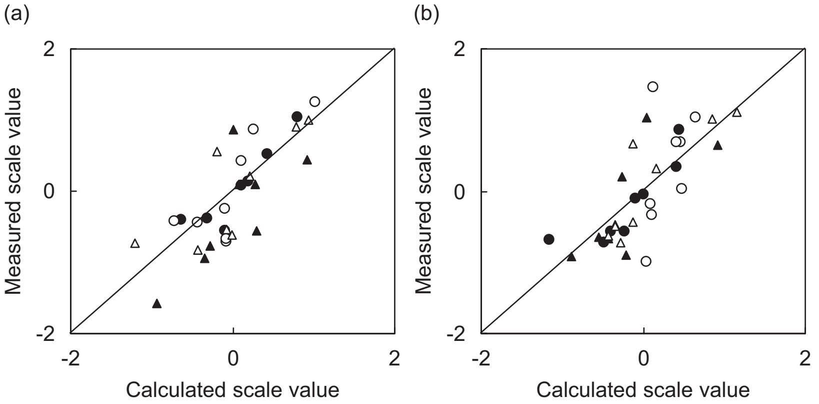

Fig. 13. Relationship between scale values obtained by annoyance judgments and scale values calculated by Eq. (5) for ACF parameters (a); and by Eq. (6) for SQ metrics (b). (●: ball, 45 dB; ○: ball, 55 dB; ▲: bang, 45 dB; and △: bang, 55 dB).

The relationship between the scale value obtained by annoyance judgments and the calculated scale value for ACF parameters are shown in Fig. 13(a). The scale values of annoyance were calculated from Eq. (5) ($r = 0.80, p < 0.01$). It was shown that temporal fluctuation of the pitch strength, as well as sound level and its fluctuation, had an effect on annoyance. Specifically, a higher sound level and larger fluctuation was associated with a higher level of annoyance.

Table 3(b) shows that for all cases, there was a positive correlation between the SQ metrics of loudness and fluctuation strength, and the scale values. Thus, these two variables were selected for the multiple regression. It was confirmed that the regression model using these metrics gave the highest regression coefficient. The standardized partial regression coefficients b_1 and b_2 in Eq. (6) were 0.63 and 0.34, respectively ($p < 0.01$ for b_1; $p < 0.05$ for b_2).

$$\mathrm{SV}_{\text{annoyance}} \approx b_1 \text{loudness} + b_2 \text{fluctuation strength}. \tag{6}$$

The relationship between the measured and calculated scale values for SQ metrics is shown in Fig. 13(b). The scale values of annoyance were calculated from Eq. (6) ($r = 0.74, p < 0.01$). Both loudness, as calculated by sound level, and its temporal variation pattern, affect annoyance. Fluctuation strength, which describes the fluctuation of the low-frequency signal, had a high correlation with both $\Phi(0)$ and VAR_$\Phi(0)$ ($r = 0.70$ for $\Phi(0)$ and $r = 0.76$ for VAR_$\Phi(0)$).

4. Discussion

Results of the ACF analysis indicated that floor and walls with sound isolators exhibited long τ_1 values ($>$29 ms), while the floors with viscoelastic damping material produced impact sounds with shorter τ_1 values (higher pitch sensation). In cases where concrete slabs and the upper layers are separated by a resilient isolator, they act independently in a rigid-body mode. In contrast, concrete slabs and upper layers connected by an adhesive viscoelastic damping material act as a single body, and thus the impact energy was absorbed in the damping layer. Moreover, increasing the resonance frequency of a floor structure effectively reduced sound levels from heavyweight impact sources. The inverse of τ_1 indicates the dominant frequency, such as the resonance frequency, of a sound. Therefore, a decreasing τ_1 was also related to the level of reduction of the heavyweight floor impact sound. Floors with viscoelastic damping material reduced sound levels, thus decreasing annoyance of the floor impact sound. Conversely, floors with resilient isolators do not always decrease annoyance.

The τ_1 values of the floor impact sounds ranged from 15–33 ms which corresponds to a frequency range from 30 to 66 Hz. Krumbholz et al. [44] and Pressnitzer et al. [45] investigated the lower limit of the residue pitch or repetition pitch. They showed that sounds with periodicities (as measured by the peak in the ACF) greater than 29 ms have virtually no pitch. The stimuli of their studies did not contain this fundamental frequency, whereas the floor impact sounds used in this study do. The test subjects could hear these low frequencies as a spectral pitch. The floor impact sound was presented by headphones. The subjects felt more oppressed by the sounds with longer τ_1 values (lower frequency).

The results of the multiple regression analysis indicated that the effects of $\Phi(0)$ and loudness were the largest among the ACF parameters and SQ metrics, respectively. Even though the value of $L_{i,\mathrm{Fmax,Aw}}$ was fixed in the subjective tests, $\Phi(0)$ and loudness changed, and affected the subjective evaluations. Different sound insulation treatments affected the sound reduction at different frequency ranges. It was found that $\Phi(0)$ and loudness, which consider all ranges of frequencies, were more suitable than $L_{i,\mathrm{Fmax,Aw}}$ for evaluating these effects. In addition, larger fluctuation strength (or $\Phi(0)$ fluctuation), which corresponds to the fluctuation of loudness, resulted in higher annoyance. The target modulation frequencies of roughness and fluctuation strength were 70 and 4 Hz, respectively. Relatively slow fluctuation, which is related more to fluctuation strength rather than to roughness, was more suitable for describing the listener's annoyance to floor impact sounds. Test results indicated that annoyance increased as $\Phi(0)$ or loudness increased. This is related to the effect of the damping material on the floor impact sound as indicated in Figs. 8a and 12a. The use of the viscoelastic damping material increases the resonance frequency of the floor slab structure and decreases the vibration acceleration level of the floor slab structure [36]. Effective reduction of the vibration acceleration level by viscoelastic damping materials resulted in a lower sound level, and thus, less annoying floor impact sounds.

Another finding obtained from the multiple regression analysis was how VAR_ϕ_1 affects annoyance. Pitch strength is represented by ϕ_1 (i.e., tonality). Variation in this value indicates the ratio of the initial and the tail parts of the impact sound. The coefficient a_3 for VAR_ϕ_1 in Eq. (5) is a negative value. Thus, a smaller variance resulted in higher annoyance. When the impact sound is not effectively reduced at the initial stage by insulation treatment, the difference between the initial and the tail parts of the impact sound becomes smaller. This means that annoyance cannot be decreased if sound properties in the initial part of the impact sound remain longer than in the tail part.

The ACF indicates how similar a signal is to a time-delayed version of itself and is useful for detecting the periodicity (regularity). The ACF analysis can describe not only a particular frequency such as the resonance frequency, but also the relationship between the resonance frequency and its harmonics. Fig. 14 shows the relationship between ϕ_1 and the difference of levels at the maximum peak and the second or the third peak. The floor impact sounds have their maximum peaks between 30 and 60 Hz. The second and the third maximum peaks appear between 60 and 100 Hz and 100 and 200 Hz, respectively. The larger level difference

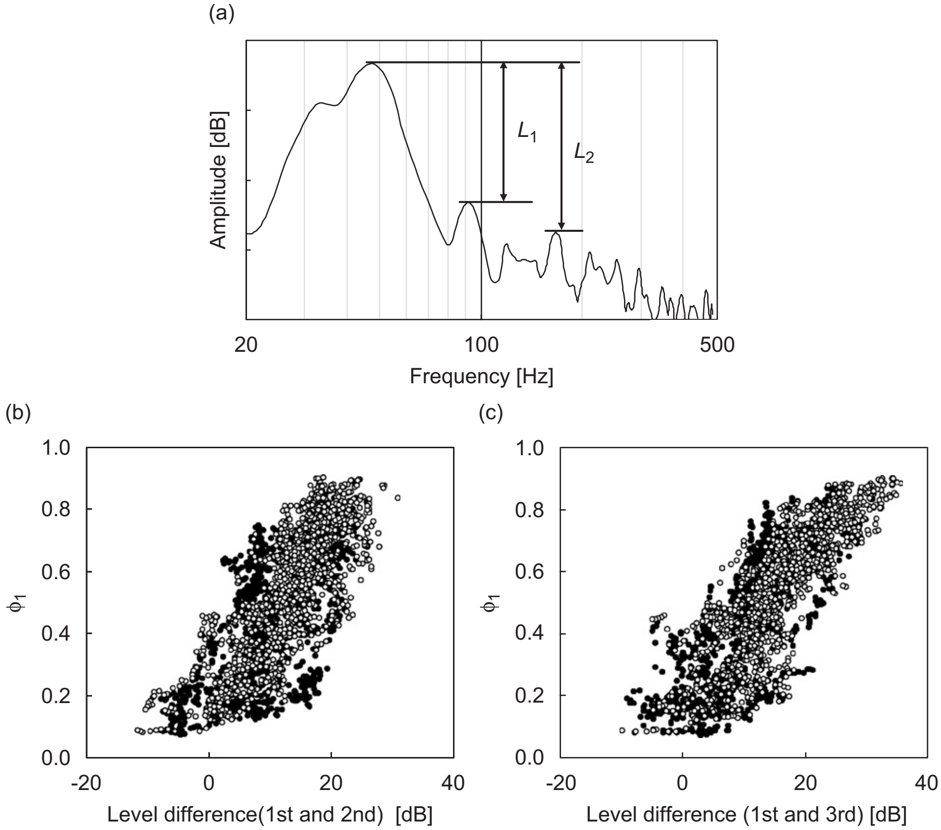

Fig. 14. Relationship between ϕ_1 and the level difference. (a) Definition of L_1, and L_2, (b) L_1, and (c) L_2 (●: ball; and ○: bang).

corresponds to a larger ϕ_1. This means that if the frequency component concentrates at a particular frequency, ϕ_1 becomes large.

SQ metrics are very useful for investigating a particular frequency band because SQ metrics include the concept of the critical band. The temporal fluctuation with relatively high-modulation frequency, like the "ratting" from a vibration-absorbing hanger, is described by roughness at relatively higher frequencies. The modulation sensation in low-frequency ranges can be described by fluctuation strength.

5. Conclusions

In order to investigate the effect of ACF parameters and SQ metrics on the annoyance of heavyweight floor impact sounds, subjective evaluations were conducted. The scale values of annoyance for different stimuli were obtained using a paired comparison method. Results of the measurements of ACF parameters and SQ metrics showed that

- τ_1 can describe the dominant frequency, such as the resonance frequency, of floor impact sounds. Sound insulation using floor and wall sound isolators resulted in a longer $\tau_{1;}$
- viscoelastic damping materials absorb the energy of heavyweight impact sounds and also reduce $\tau_{1;}$
- while loudness for the bang machine was greater than that for the impact ball, sharpness for the bang machine was smaller than that for the impact ball. Viscoelastic damping materials installed in the floor reduced loudness and increased sharpness.

Observations regarding the relationship between annoyance and the ACF parameters and SQ metrics show that

- annoyance due to heavyweight floor impact sound was highly correlated with $\Phi(0)$ and loudness, even though the sound level was fixed at a constant $L_{i,\mathrm{Fmax,Aw};}$
- In addition to the noise level, ACF parameters are measures for calculating annoyance. The factors important for evaluating annoyance were $\Phi(0)$ and fluctuations in $\Phi(0)$ and $\phi_{1;}$
- among the SQ metrics, the important factors for evaluating annoyance were loudness and fluctuation strength.

Acknowledgments

This work was supported by Grant no. 03-1-11-002 from the Core Environment Technology Development Project for the Next Generation of the Korea Ministry of Environment, and Grant no. 10023489 from the Standardized Technology Development Project of Ministry of Commerce, Industry, and Energy. The authors thank Dr. Jeong Ho Jeong, Dr. Young Jeong, and Mr. Seung Yup Yoo, who conducted the subjective tests and the field measurements. They also appreciate the careful reading of the manuscript by the reviewers and their helpful comments in revising this paper. The authors would also like to thank the subjects who participated in this study.

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